Demonstration of Range & Doppler Compensated Holographic Ladar

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Presented by Piotr Kondratko

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Outline

• Digital Holography Overview and Applications

• Study Problem and Objective

• System Architecture and Design

• Controller Software System Overview

• Tracker Performance

• Field Tests and Results
Digital Holography Background

- Form holograms by interfering signal with off-axis reference beam
  - Use COTS focal plane arrays (CCD/CMOS) to record data
- Numerically process & filter to obtain complex-valued images
- Access to image phase permits advanced functions
  - Aberration correction / wavefront sensing, multi-aperture / synthetic aperture imaging, 3D and vibration imaging

DH System Implementation
(Bi-static or Monostatic)

Transmitter

Receiver

Laser

FPA

Local Oscillator

Pupil Plane

Hologram

2D FFT

Pupil

LO

Complex Image

Phase Correction

Sharpened Image
## Applications of Digital Holography

### Combined Coherent Imaging
- QL sensitivity → less laser power or > range
- Corrected imaging → improved imaging
- Dual wavelength → advanced imaging

### Aberration Correction & WFS
- Robust against scintillation
- Does not require a separate illuminator
- Multi-plane WFS → deep turbulence correction

### Multi & Synthetic Aperture Imaging
- DH enables phased array imaging
- High resolution imaging
- Lower SWaP

### 3D, Vibration & Polarimetric Imaging
- 3D range & pose
- Vibration and Polarization Imaging
- Biometrics ID
The Problem Statement

Relative motion between ladar and target $\rightarrow$ integration efficiency: $\eta_{\chi}$

DH system efficiency loss associated with
- Temporal Signal and LO alignment $\rightarrow \tau$
- Frequency difference due to Doppler $\rightarrow f_D = 2v/\lambda$

$\eta = [1 - (\tau / t_p)]$

$\eta = sin^2c(2\pi f_D t_p)$

$CNR = \eta \frac{\lambda^3}{hc} T^2 \left( \frac{\rho}{\Omega} \right) \frac{P_{tp}}{\pi \omega^2}$
**Demonstration Objective**

- Demonstrate range and Doppler compensation technique for a moving target
- **Location:** Wright Patterson AFB
- **Time:** May 2015
- **CNRs:** ~8 to 24 dB (pulse width and target reflectivity)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TX Peak Power</td>
<td>500 mW</td>
</tr>
<tr>
<td>Wavelength (λ)</td>
<td>1545 nm</td>
</tr>
<tr>
<td>Pulse width (t&lt;sub&gt;p&lt;/sub&gt;)</td>
<td>100 - 300 ns</td>
</tr>
<tr>
<td>Target max speed (v)</td>
<td>±~20 m/s (±45 mph)</td>
</tr>
<tr>
<td>Target range (R)</td>
<td>200-1000 m</td>
</tr>
<tr>
<td>Target reflectivity (ρ/Ω)</td>
<td>Retro Tape 1: 89 (sr&lt;sup&gt;-1&lt;/sup&gt;)</td>
</tr>
<tr>
<td></td>
<td>Retro Tape 2: 8 (sr&lt;sup&gt;-1&lt;/sup&gt;)</td>
</tr>
<tr>
<td>Aperture</td>
<td>27.5 cm (11”)</td>
</tr>
<tr>
<td>System efficiency (η)</td>
<td>6%</td>
</tr>
<tr>
<td>One-way atmospheric transmission (T)</td>
<td>96%</td>
</tr>
</tbody>
</table>
DH Imager System Architecture

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal length</td>
<td>11.9 m</td>
</tr>
<tr>
<td>FOV at 500 m</td>
<td>32 cm</td>
</tr>
</tbody>
</table>

Physical layout of designed system

- Optical axis height above breadboard determined by telescope: 6 - 7"
- Transmit lens pair ("beam expander") expands beam for safety, and allows flexibility to adjust divergence for beam size on target
Functional Diagram of DH System

Acquire Range
- Direct Detection
- Laser Range Finder

Filter Noise and Estimate (Kalman)
- Target Distance
- Target Velocity

Adjust the DH System $f_D = 2v/\lambda$
- Frequency AOFS
- Pulse Positions
Field Testing and Target

DH Range & Doppler Demonstration System

Target on Runway

Illumination Scheme
Tracker Performance

Range:
1 cm → 67ps (small fraction from 300ns pulse)

Doppler:
Measured > 1 m/s → 55% Efficiency
Filtered ~0.05 m/s → 99% Efficiency

Range less important than Doppler filtering
DH Ranging Results

- Approximate Vehicle Target Velocities: 5, 10, 13, 16, 24 m/s

- Model includes range dependent vignetting

\[ CNR = \eta \frac{\lambda^3}{hc} T^2 \left( \frac{\rho}{\Omega} \right) \frac{P t_p}{\pi \omega^2} \]

No CNR loss due to range and Doppler was observed
System configured (automated) to validate range and Doppler ambiguity function

- target is fixed at range
- sweep programmed range and Doppler

\[ \eta \chi(t, f) = \frac{|\chi_{u,v}(t, f)|^2}{E_u E_v} \]

\[ T = \begin{cases} 
T_v & t_d \leq (T_u - T_v) / 2 \\
(T_u + T_v) / 2 - t_d & (T_u - T_v) / 2 < t_d \leq (T_u + T_v) / 2 \\
0 & (T_u - T_v) / 2 < t_d 
\end{cases} \]

\[ \eta \chi(t_d, f_d) = \frac{T^2}{T_u T_v} \text{sinc}^2(f_d T) \]
Summary and Future Work

• Digital Holography Ladar → Demonstration of range and Doppler compensation

• System capability → complete efficiency recovery at ~24 m/s vehicle target speeds from ~200-700m

• Demonstration confirmed range and Doppler ambiguity model

Future Work:

• Range and Doppler compensation for multi-aperture DH RX/TX systems for ground and air platforms

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Software and Timing Architecture

**Host PC**
- **HOST Main**
  - 20 Hz Non-Deterministic
  - Control the Real-Time States
  - Display Data
  - Log Data

**Real-Time Controller**
- **RT Main: Acquisition, Track, & Point**
  - 50 Hz Deterministic
  - ULS Range
  - Filter and Track
  - Send Range Track Data to DG535 Thread
  - Send Velocity Data to AO Thread
  - Send Info to Host

**Data Producer**
- 50 Hz Non-Deterministic
  - Receive data and status from the real-time system
  - Plot data to the user

**Data Logger**
- As-fast-as-possible Non-Deterministic
  - Log data and status to disk

**DG-535 Thread (GPIB)**
- 25 Hz Non-Deterministic
  - Update All Delays (In Standby)
  - Range Delay Calculation
  - Send Delay Data to DG535 on Channel C

**AO Thread (DAQmx)**
- 50 Hz Deterministic
  - Doppler Calculation
  - Send AO Data to DAQ
  - Receive Ack

**States:**
- Initialize
- Error
- Standby
- Acquire Only
- Acquire&Track
- Stop

**States:**
- Initialize
- Standby
- Track
- Error
- Stop

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**Doppler Compensation Demonstration Timing Diagram**

- T0
- AB
- TX-AOM
- CD
- LO-AOM
- DG535-1
- AB-Camera
- Cam. Integration

- 0.3us
- Track Range